Observations of Dynamic Traffic Flow Phenomena on a German Autobahn

Presented by:
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February 17, 2006
Objectives

- Describe data
- Identify bottleneck activations
- Measure of queue discharge features
- Examine potential bottleneck activation triggers
- Conclusions and Implications
Data – A5 North of Frankfurt am Main

- Inductive loop detectors
- 1-minute resolution
- Count and speed in each lane for autos and trucks
- No fixed auto speed limit
- Trucks limited to right lane and 80 km/h
- No ramp metering
Background

- 50 years of freeway bottleneck studies
  - Manually collected data (direct observation, air photos)
  - Limitations of the data analysis methods
    - Short duration
    - Studies at fixed points
    - Lacking activation criteria

- Recent studies of Canadian, British, and US freeways employed more robust data analysis methods – none on German freeways
- Measured variables (velocity and flow) exhibit statistical variations as well as time-dependant changes

- These plotting techniques makes it difficult to distinguish between the two
Motivation

- Kerner’s work:
  - Limited number of days and bottlenecks
  - Did not define bottleneck spatial & temporal limits
  - Has not made his data available to other researchers
- This research was motivated by the need for independent analysis of German freeway dynamics
- For the **first time**, German freeway was available for this study
Method - Plot Sensor Data Cumulatively

$N(x,t)$

Flow Increase

Flow Decrease

Slope = number/time = FLOW

Travel Direction

Time, $t @ x$
Method - Plot A5 Count Data Cumulatively

A5 • Station D21

N(x,t) Cumulative Count

Time

13:30 13:40 13:50 14:00 14:10 14:20 14:30

0 500 1,000 1,500 2,000 2,500 3,000 3,500 4,000 4,500 5,000
Choose Oblique Scaling Rate

\[ N(x,t) \]

\[ q_0 = 4910 \text{ vph} \]
Prepare Oblique Axis

A5 • Station D21

$N(x,t)$

$q_0 = 4910$ vph

$N(x,t) - q_0 t'$
Oblique Axis Plot

A5 - Station D21

$N(x,t) - q_0 t'$

$N(x,t) - q_0 t'$
Annotate with Linear Approximations

A5  Station D21

$N(x,t)-q_0t'$

- 5510 vph
- 4220 vph
- 4960 vph
- 4060 vph
- 5230 vph

Time

13:30 13:40 13:50 14:00 14:10 14:20 14:30
Queueing Diagram

$N(x_j, t)$

Travel Direction

$x_1$

$N(x_1, t)$

Time, $t$
Queueing Diagram

Ref. Veh. Trip Time

Time, t

Travel Direction

N(x_1, t)

N(x_2, t)
Queueing Diagram

\[ N(x_j, t) \]

Travel Direction

Ref. Veh. Trip Time

Time, \( t \)

\[ N(x_1, t) \]

\[ N(x_2, t) \]

Trip Time, \( t_1 \)

Number of vehicles
Queueing Diagram

\[ N(x_j, t) \]

\[ x_1 \quad \text{Travel Direction} \quad x_2 \]

\[ N(x_1, t) \]
\[ N(x_2, t) \]

Time, \( t \)
Queueing Diagram

Travel Direction

Excess Accumulation

Excess Travel Time = Delay

\[ N(x_1, t) \]

\[ N(x_2, t) \]
Method

- Transformed curves of vehicle arrival number vs. time and time-averaged velocity vs. time provide fidelity required to identify key time-dependent traffic features related to active bottlenecks.
- **Active** bottleneck exists when upstream traffic is queued and downstream traffic unqueued.
- Deactivation occurs with a decrease in flow or when a queue spills back from a downstream bottleneck.
Queueing Diagram – A5 Data

Time, $t @ D20$

Legend:

- Black
- Red
- Blue
- Green

Bottleneck

$N(x, t) - q_0 = 4,300$ vph
Diverge Activation

\[ N(x,t) - q_0 = 4,300 \text{ vph} \]

LEGEND

D20 D21 D22 D23 D24
Diverge Activation

\[ N(x,t) - q_0 = 4,300 \text{ vph} \]

LEGEND

Bottleneck

14:02 D22

14:00

13:40 13:45 13:50 13:55 14:00 14:05 14:10

Time, \( t \) @ D20
Diverge Activation

\[ N(x,t) - q_0t' = q_0 = 4,300 \text{ vph} \]

**LEGEND**

- D20
- D21
- D22
- D23
- D24

**Time, \( t @ D20 \)**

- 13:40
- 13:45
- 13:50
- 13:55
- 14:00
- 14:05
- 14:10

- 3900 vph
- 5290 vph
Diverge Activation

[Diagram showing time, t @ D22, with velocities 95 km/h and 45 km/h, and a bottleneck indicated.]
Diverge Activation

Time, $t$ @ D20

$N(x,t) - q_0 t' \quad q_0 = 4,300 \text{ vph}$

LEGEND

D20  D21  D22  D23  D24
Diverge Activation

\[ N(x,t) - q(t) = 4,300 \text{ vph} \]

**LEGEND**

- D20
- D21
- D22
- D23
- D24

Time, \( t @ D20 \)

Time, \( t @ D21 \)

Bottleneck
Diverge Activation

N(x,t)-q_0^t \quad q_0 = 4,300 \text{ vph}

LEGEND

D20  D21  D22  D23  D24

Bottleneck

Time, t @ D20
Diverge Activation

\[ N(x,t) - q_0t', \quad q_0 = 4,300 \text{ vph} \]

\[ V(D20,t) - v_0t', \quad v_0 = 4,830 \text{ km/h}^2 \]

LEGEND

D20  D21  D22  D23  D24
Diverge Deactivation

\[ N(x,t) - q_0 t', q_0 = 4,300 \text{ vph} \]

Time, \( t @ D20 \)
Diverge Deactivation

Time, $t @ D22$

$V(D22,t) - v_0 t'$  
$v_0 = 5,615 \text{ km/h}^2$

Time, $t @ D20$

$N(x,t) - q_0 t'$  
$q_0 = 4,300 \text{ vph}$

LEGEND

D20  D21  D22  D23  D24
Bottleneck Outflow

$N(D23,t)$, $q_0 = 4,730$ vph

Time, $t$ @ D23
Bottleneck Outflow

Bottleneck C1

N(D23,t) - q_0 t' = 4,730 vph

15.4%
Bottleneck Outflow

\[
N(D23,t) - q_0 t' = 4,730 \text{ vph}
\]

Bottleneck C1

\[
\text{Bottleneck Outflow}
\]
Bottleneck Outflow

\[ V(D23, t) - v_t' V_0 = 4,800 \text{ km/h}^2 \]

\[ V(D23, t) - q_0 t' q_0 = 4,730 \text{ vph} \]

Time, \( t \) @ D23

Bottleneck C1

D22/D23

10.8%
Bottleneck Outflow

Bottleneck C1

- Sept. 14, 2001
- Active 14:02-14:17 between D22 and D23
- Outflow measured at D23

<table>
<thead>
<tr>
<th>Lane</th>
<th>Flow (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>4,630</td>
</tr>
<tr>
<td>Left</td>
<td>1,840</td>
</tr>
<tr>
<td>Mid</td>
<td>1,640</td>
</tr>
<tr>
<td>Right</td>
<td>1,150</td>
</tr>
</tbody>
</table>
Diverge Bottleneck Characteristics

- A diverge bottleneck arose between D22 and D24 a total of 21 times over six days
- Durations ranged from 7 to 223 minutes
- Discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>4,890</td>
<td>310</td>
</tr>
<tr>
<td>Left</td>
<td>1,970</td>
<td>120</td>
</tr>
<tr>
<td>Mid</td>
<td>1,700</td>
<td>130</td>
</tr>
<tr>
<td>Right</td>
<td>1,220</td>
<td>100</td>
</tr>
</tbody>
</table>

n=21
Isolated Diverge Bottleneck Characteristics

- 12 diverge bottleneck activations were preceded by periods of large pre-queue flows – “isolated”
- “Isolated” discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Condition</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
<th>Flow Drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Pre-queue</td>
<td>5,110</td>
<td>290</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>4,890</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>Pre-queue</td>
<td>2,160</td>
<td>190</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,980</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>Pre-queue</td>
<td>1,740</td>
<td>160</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,700</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>Pre-queue</td>
<td>1,210</td>
<td>130</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,210</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

n=12
Bottleneck Inflow

Left
\( v_0 = 30 \text{ trucks/hr} \)

Mid
\( v_0 = 80 \text{ trucks/hr} \)

Right
\( v_0 = 400 \text{ trucks/hr} \)

Time, \( t @ D22 \)
Bottleneck Inflow

Left $q_0=1,800$ vph
Mid $q_0=1,800$ vph
Right $q_0=1,600$ vph
## Isolated Diverge Bottleneck Triggers

<table>
<thead>
<tr>
<th>Date</th>
<th>Bottleneck No.</th>
<th>Off-ramp Flow Surge</th>
<th>High Pre-Queue Flow All Lanes (vph)</th>
<th>High Pre-Queue Flow Right Lane (pc/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 19</td>
<td>G14</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Sep. 14</td>
<td>C1</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Sep. 14</td>
<td>C2</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Sep. 14</td>
<td>C8</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Dec. 4</td>
<td>F2</td>
<td></td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Dec. 4</td>
<td>F9</td>
<td></td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Sep. 20</td>
<td>E3</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Aug. 17</td>
<td>B2</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Aug. 17</td>
<td>B7</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Aug 17</td>
<td>B8</td>
<td></td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>May 18</td>
<td>A1</td>
<td></td>
<td>☑</td>
<td>☑</td>
</tr>
</tbody>
</table>
Diverge Bottleneck Deactivation

- 2 “isolated” diverge deactivations observed between D22 and D24 over 6 days

**Triggers**
- Off-ramp flow drop (all vehicles)
- D25 right lane flow drop (trucks)
Diverge Bottleneck Deactivation

Time, $t @ D25$

N(D25,t) - $q_0^t$

520 vph
750 vph
520 vph
310 trucks/h

31%

440 trucks/h

30%

17:36 B7 Deactivation

310 trucks/h

17:36 B7 Deactivation

Off-Ramp
$q_0 = 590$ vph

Right
$q_0 = 350$ trucks/h
Merge Bottleneck Characteristics

- A merge bottleneck arose between D7 and D8 a total of 12 times over six days
- Durations ranged from 7 to 73 minutes
- Discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>5,040</td>
<td>420</td>
</tr>
<tr>
<td>Left</td>
<td>2,090</td>
<td>200</td>
</tr>
<tr>
<td>Mid</td>
<td>1,840</td>
<td>170</td>
</tr>
<tr>
<td>Right</td>
<td>1,110</td>
<td>90</td>
</tr>
</tbody>
</table>

n=12
### Isolated Merge Bottleneck Characteristics

- 2 merge bottleneck activations were preceded by periods of large pre-queue flows – “isolated”
- “Isolated” discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Condition</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
<th>Flow Drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Pre-queue</td>
<td>5,260</td>
<td>60</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>5,130</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>Pre-queue</td>
<td>2,250</td>
<td>70</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>2,220</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>Pre-queue</td>
<td>1,920</td>
<td>40</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,840</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>Pre-queue</td>
<td>1,100</td>
<td>50</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,070</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

n=2
Merge Activation Triggers

- D6 on-ramp flow surge
- Net lane change to left (D7-D8)
Merge Activation Trigger

![Graph showing traffic flow and activation times]

- Merge Activation Trigger Time, $t @ D6$
- $N(D6on,t) = q^0 - q^0t, q^0 = 1,570 vph$
- 14:30 E2 Activation
- 15:08 E2 Activation
- 15:00 Time, $t @ D6$
- 26% Traffic Reduction
Merge Activation Trigger

Graph showing the net lane change, N(D7-D8), over time at D7.

- **Left Lane**:
  - 1 veh/min
  - -2 veh/min

- **Mid Lane**:
  - -1 veh/min
  - 6 veh/min
  - -1 veh/min
  - 5 veh/min
  - 0 veh/min

- **Right Lane**:
  - -3 veh/min

Graph indicates changes in vehicle flow and lane changes at different times, starting from 15:00 to 15:20. The bottleneck is marked at D8, and the time of activation is noted at 15:08 E2.
Conclusions

- Bottlenecks at **predictable** locations:
  - Merge and diverge areas

- Discharge flows:
  - **Reproducible** across all lanes and lane by lane
  - **Nearly constant** and should be viewed as the bottlenecks’ capacities

- “**two capacity**” theory was validated:
  - in both merge and diverge locations, bottleneck discharge flows were lower than pre-activation flows
Conclusions

- Traffic disturbances:
  - Nearly constant speeds
  - Traveled long distances (20 km) without spreading
- Merge bottlenecks triggers:
  - Increased on-ramp flows
  - Lane changing to the left
- Diverge bottlenecks triggers:
  - Increased off-ramp flows
  - High pre-queue flows in all lanes with notable truck influence in the right lane
Implications/Future Research

- **Unique evaluation** of truck and auto data:
  - Allowed detailed study of bottleneck triggers
- The results of this study should be used to **calibrate**, then **validate** both macroscopic and microscopic traffic flow models of the A5
- The extent to which **speed limits**, both fixed and variable, affect bottleneck formation, should be studied
- The impact of **variable message signs** on congested traffic should also be studied
Acknowledgements

- Robert Bertini & the ITS Laboratory Team at Portland State University
- Hessian National Office for Road and Traffic
- Institute for Economics and Traffic at Technical University - Dresden
- Department of Civil & Environmental Engineering at PSU
- Department of Civil Engineering & Geomatics at Oregon Institute of Technology